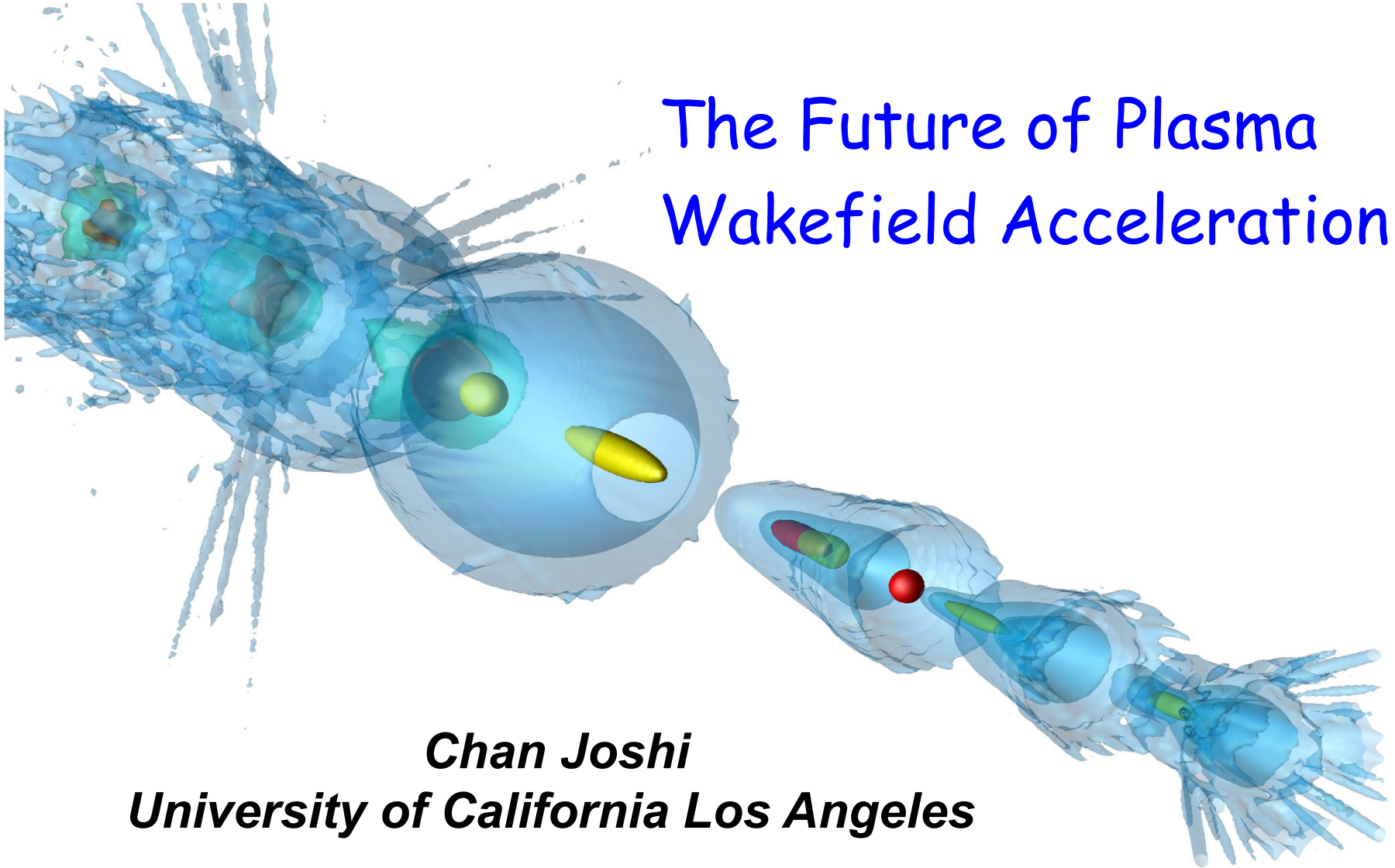


The Future of Plasma Wakefield Acceleration



Chan Joshi
University of California Los Angeles

Fermi national Accelerator Lab May 24 2011

UCLA

Plasma Accelerator Group
Founded 1980

**UCLA Program on
Plasma Based Accelerators**

C. Joshi, P.I.
W. Mori, Co-P.I.
C. Clayton, Co-P.I.
2009-Present

Administration
M. Guerrero

EXPERIMENTS

Dr. Chris Clayton
Dr. Sergei Tochitsky

Ken Marsh

Dan Haberberger (11)

Chao Gong

Navid Vafaei (New)

Jeremy Pigeon (New)

Jessica Shaw(New)

THEORY & SIMULATIONS

Professor Warren Mori

Weiming An (12)

Asher Davidson (13)

Yu Peicheng

Collaborators:

Professors Rosenzweig & Pellegrini (UCLA)

Dr. M. Hogan (SLAC)

Professor Luis Silva (IST)

Glenzer, Froula, Pollock (LLNL)

Wei Lu (Tsinghua U)

Support: DOE HEP and NSF

Plasma Accelerators

"Story of Science as a living thing" J.M.Dawson

1979 Tajima & Dawson Paper

1981 Tigner (HEPEP sub-Panel)
recommended investment in advanced
acceleration tech's.

1985 Malibu, GV/m *unloaded* beat wave
fields, world-wide effort begins

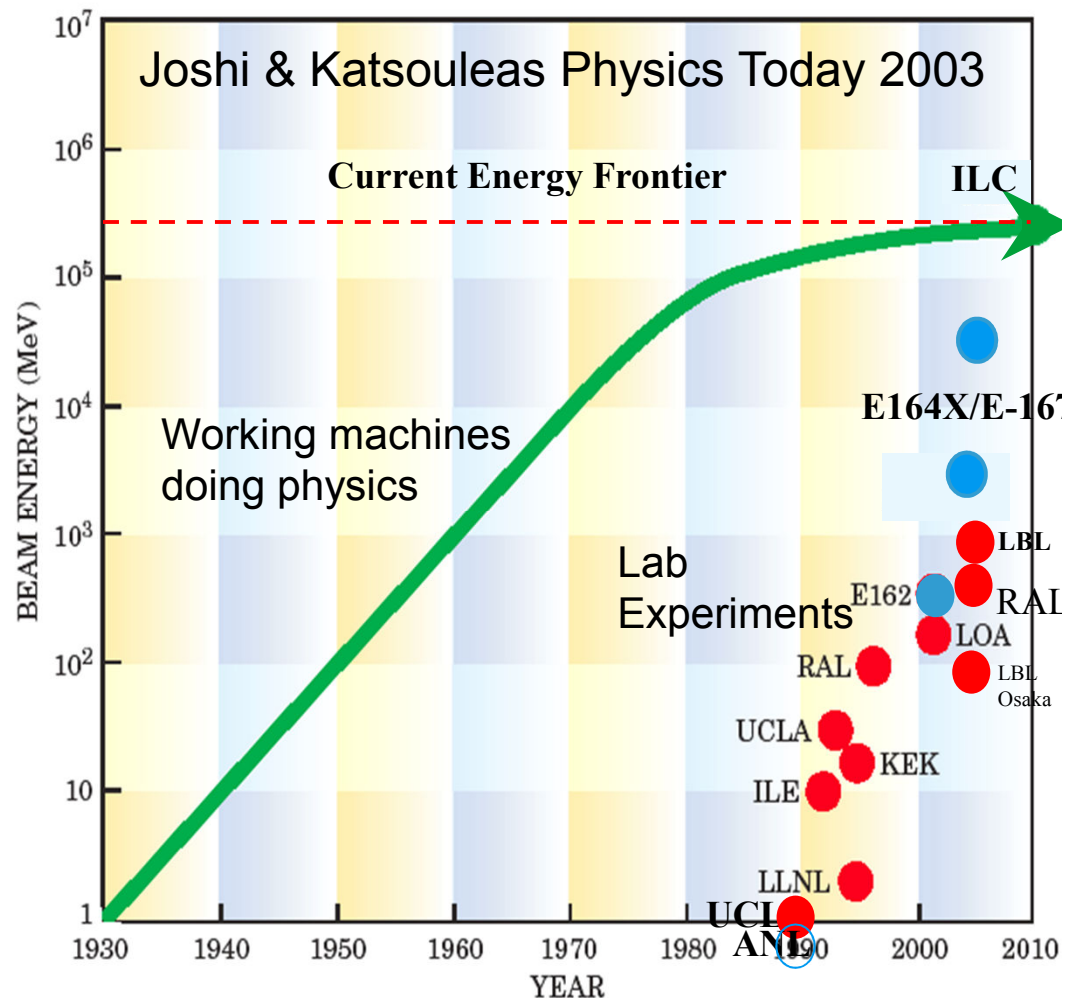
1988 ANL maps beam wakes

1992 1st e- at UCLA beat wave

1994 'Jet age' begins (100 MeV e- by
Self-modulation at RAL)

2004 'Dawn of Compact Laser
Accelerators' (monoenergetic beams at
LBNL, LOA, RAL)

2007 Energy Doubling at SLAC by
E167 : UCLA/SLAC/USC



Need a new technology for accelerating charged-particles



Fermilab's Early Interest in Advanced Accelerators

- * 1982 First laser Acceleration of Particles Workshop: Lee Teng, Frank Cole, Fred Mills, Dave Nauffer, Russ Huson
- * 1982 UCLA's proposal for Plasma Acceleration reviewed by Teng and Cole: My first visit to Fermilab to give a colloquium to explain the concept.
- * 1985 Lee Teng Chairs Second LAP Workshop Malibu
- * John Peoples attends the 1992 Workshop on Acceleration of Charged Particles in Astrophysical and laboratory Plasmas, Kardamily Greece.
- * PWFA experiments at A0 facility, Fermilab 1999-2005

Plasma Based Accelerators

- **Laser Wake Field Accelerator**

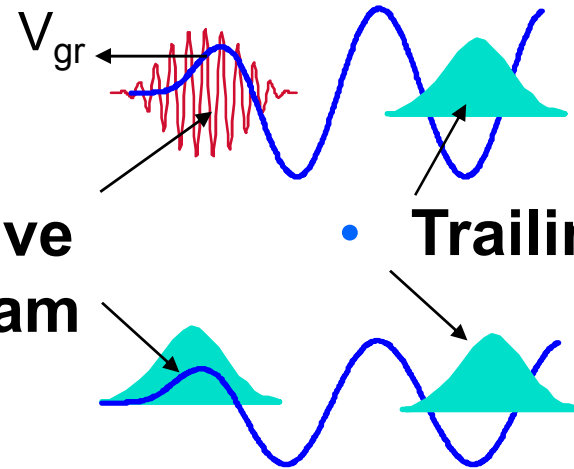
A single short-pulse of photons

Plasma Wake Field Accelerator

A high energy electron bunch

- **Drive beam**

- **Trailing beam**



- Wake: phase velocity = driver velocity

Large wake for a laser amplitude, $a_0 = eE_0/m\omega_0 c \sim 1$ or a beam density $n_b \sim n_0$

For τ_{pulse} of order $\pi\omega_p^{-1} \sim 100\text{fs}$ ($10^{17}/n_0$)^{1/2} and spot size c/ω_p :

$P \sim 15 \text{ TW}$ ($\tau_{pulse}/100 \text{ fs}$)² laser
 $I \sim 20 \text{ kA}$ Beam

T.Tajima and J.M.Dawson PRL(1979)
 P.Chen et.al.PRL(1983)

Conventional Accelerator

Copper Structure with irises

Powered by microwaves

Energy Gain 20 MV/m

Structure Diameter 10cm

Plasma Accelerator

Ionized Gas

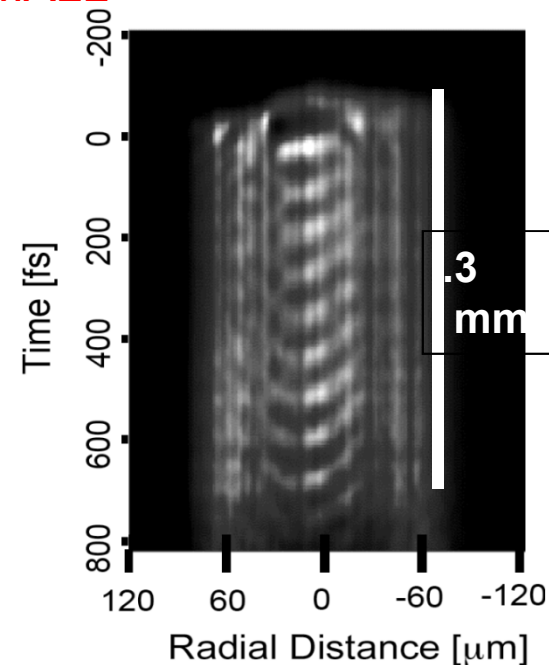
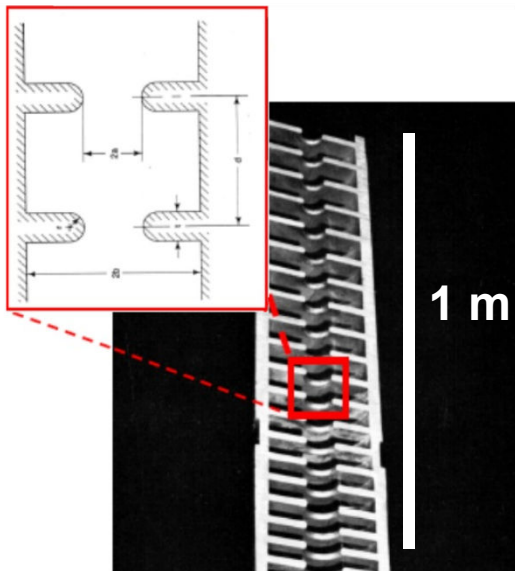
Lifetime, few picoseconds

*Powered by a Laser or
electron beam pulse*

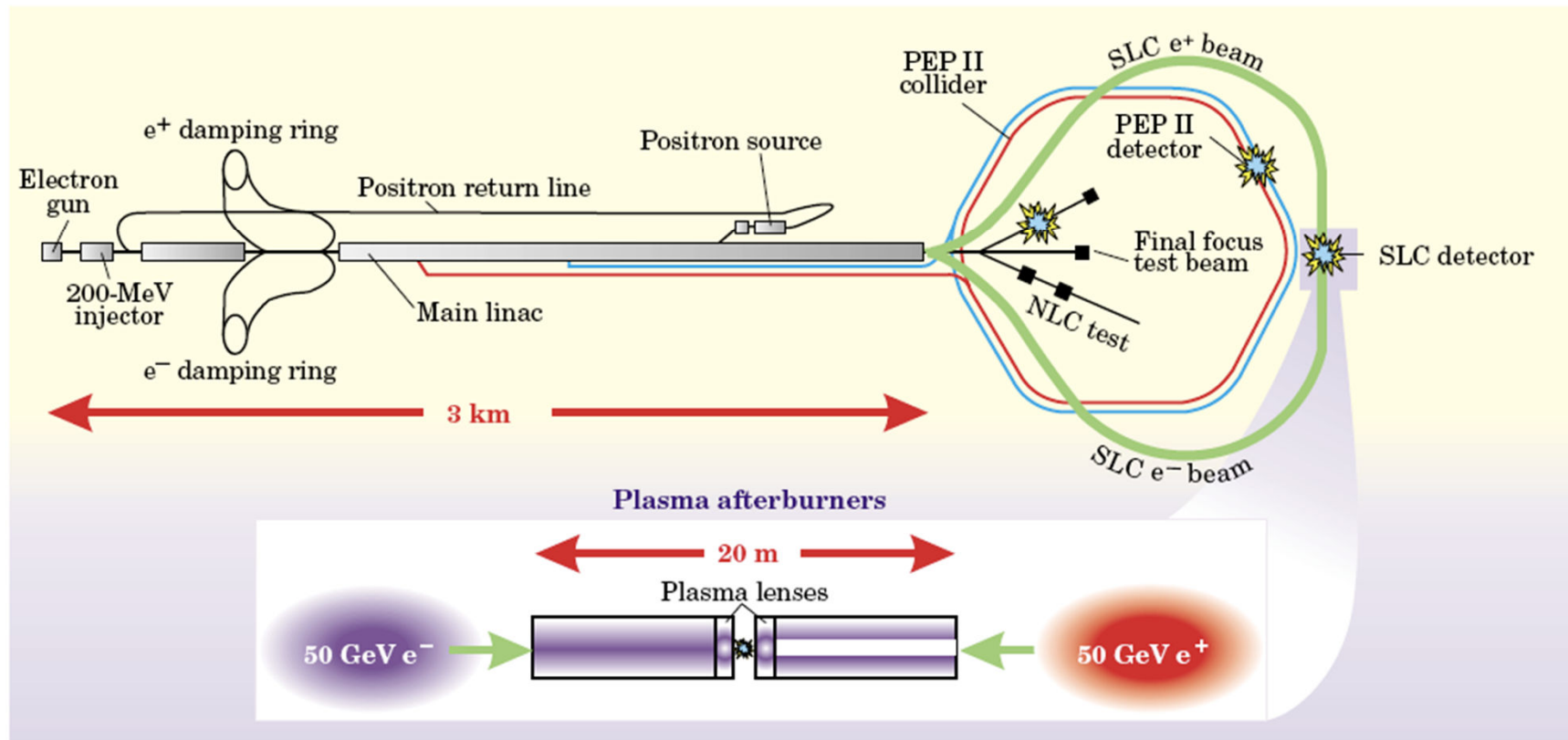
Energy Gain 20 GV/m

Diameter 0.1-1 mm

BIG PHYSICS BECOMES SMALL



Plasma Afterburner for Linear Collider

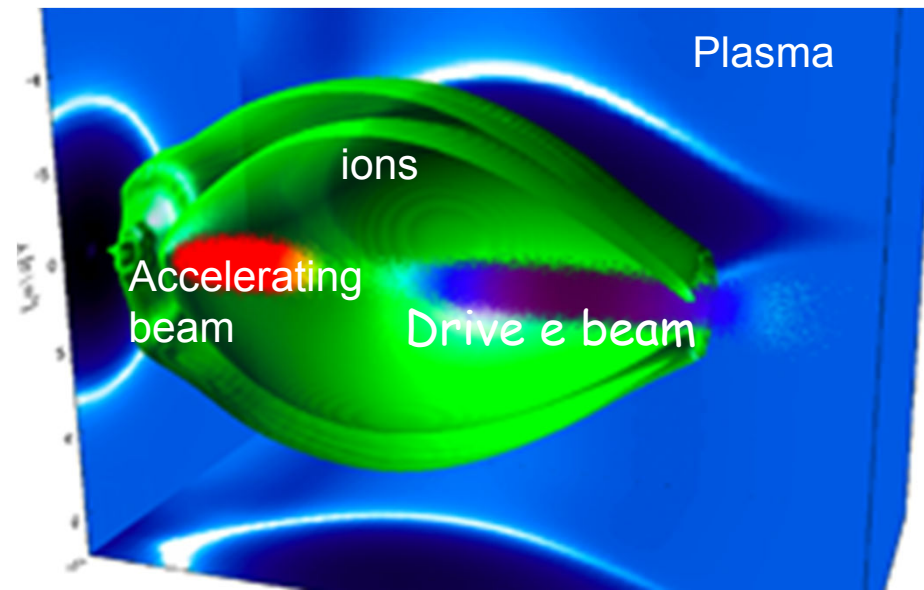


100 GeV x 100 GeV e^+e^- collider 10^{32} Luminosity

C.Joshi and T. Katsouleas Physics Today 2003



Plasma Wakefield Acceleration



- Space charge force of the beam pulse displaces plasma electrons
- Plasma ion channel exerts restoring force => space charge wake

No dephasing between the particles and the wake

OUR VISION



To address critical issues for realizing a plasma-based accelerator at the energy frontier in the next decade. A by-product will be compact accelerators for industry & science

Plasma Wakefield Acceleration

O
n
l
y

$$N = 4 \times 10^{10}$$

Energy 50 GeV

p

Rep Rate 60 HZ

a

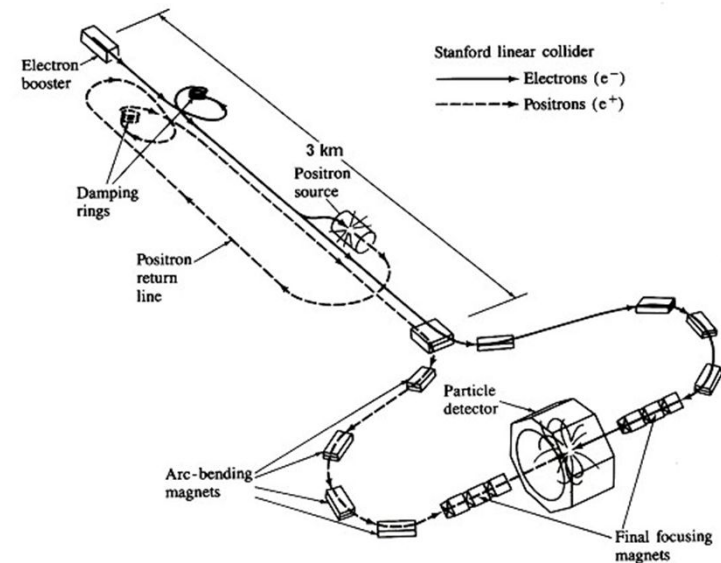
Energy/pulse 320 J

Focal Spot Size 10 microns

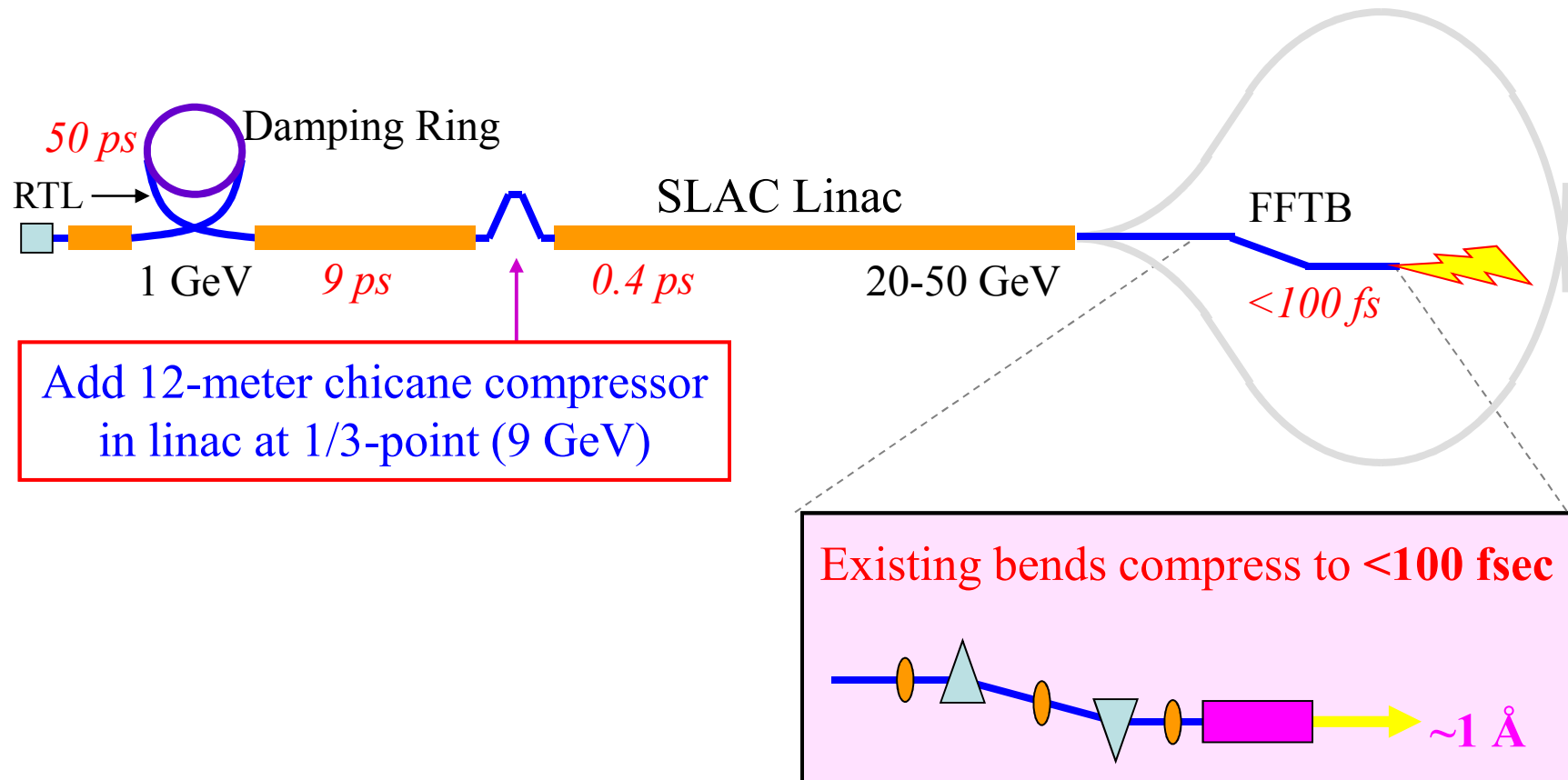
Pulse Width 50 fs

Focused Intensity $7 \times 10^{21} \text{ W/cm}^2$

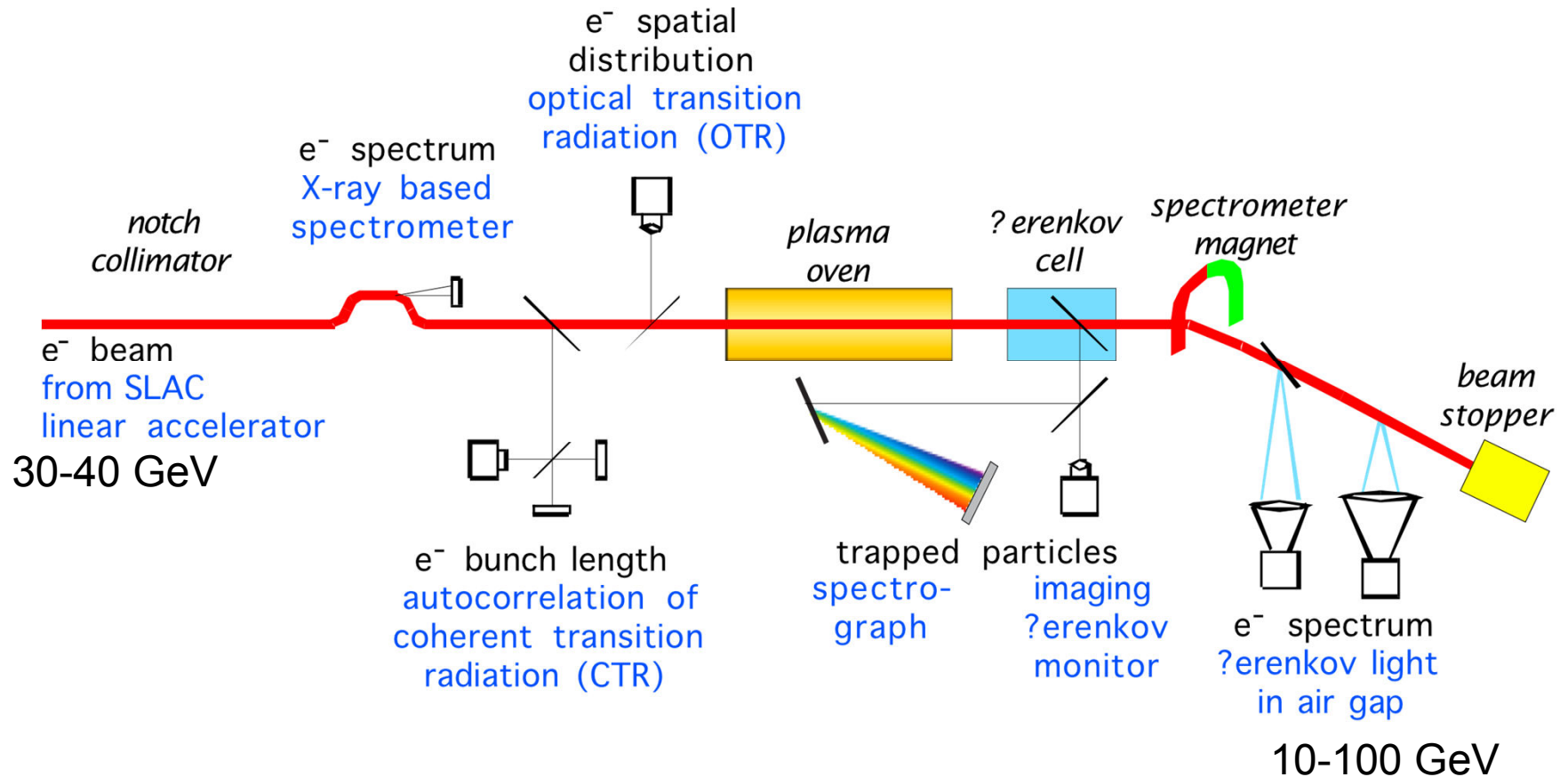
Comparable to the most intense laser beams to-date



Short Bunch Generation In SLAC Linac

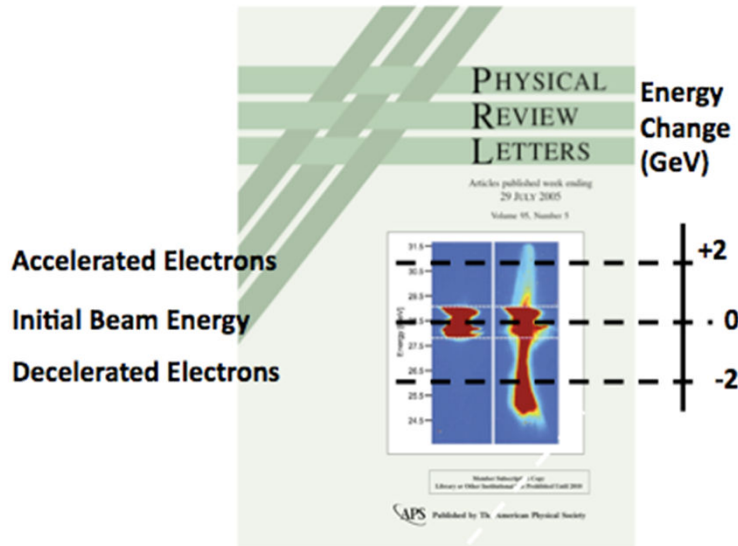


Experimental Setup

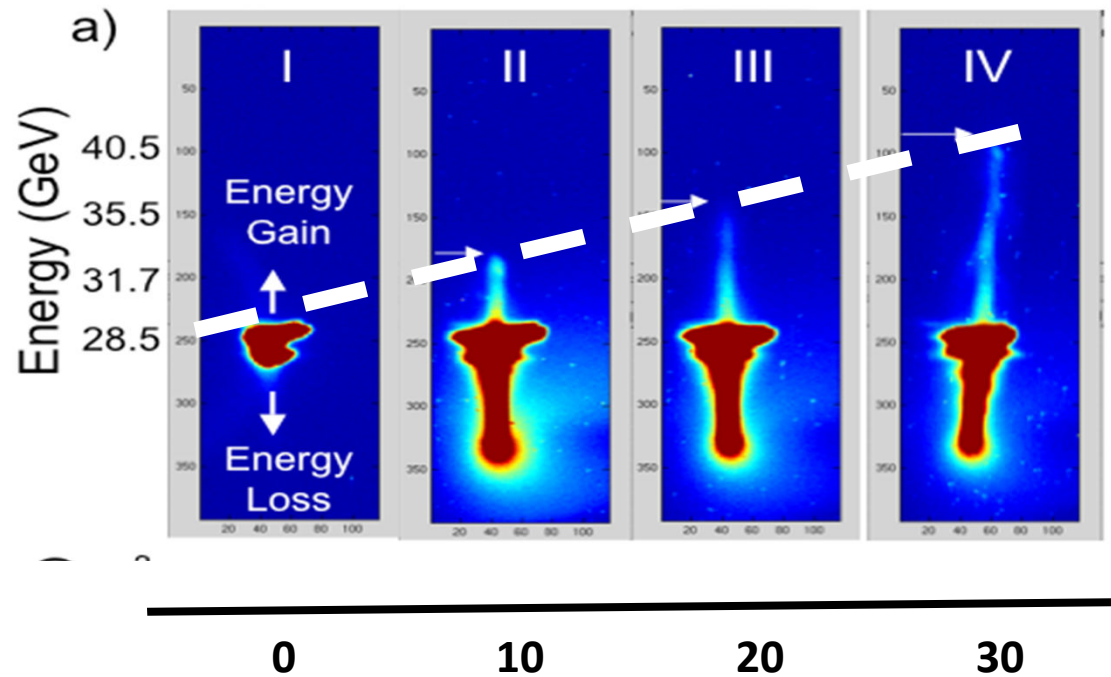




Energy Gain Scales Linearly with Length



$$n_e \approx 3.5 \times 10^{17} \text{ cm}^{-3}, L \approx 10 \text{ cm}, N \approx 1.8 \times 10^{10}, \tau \approx 50 \text{ fs}$$



BREAKING THE 1 GeV BARRIER

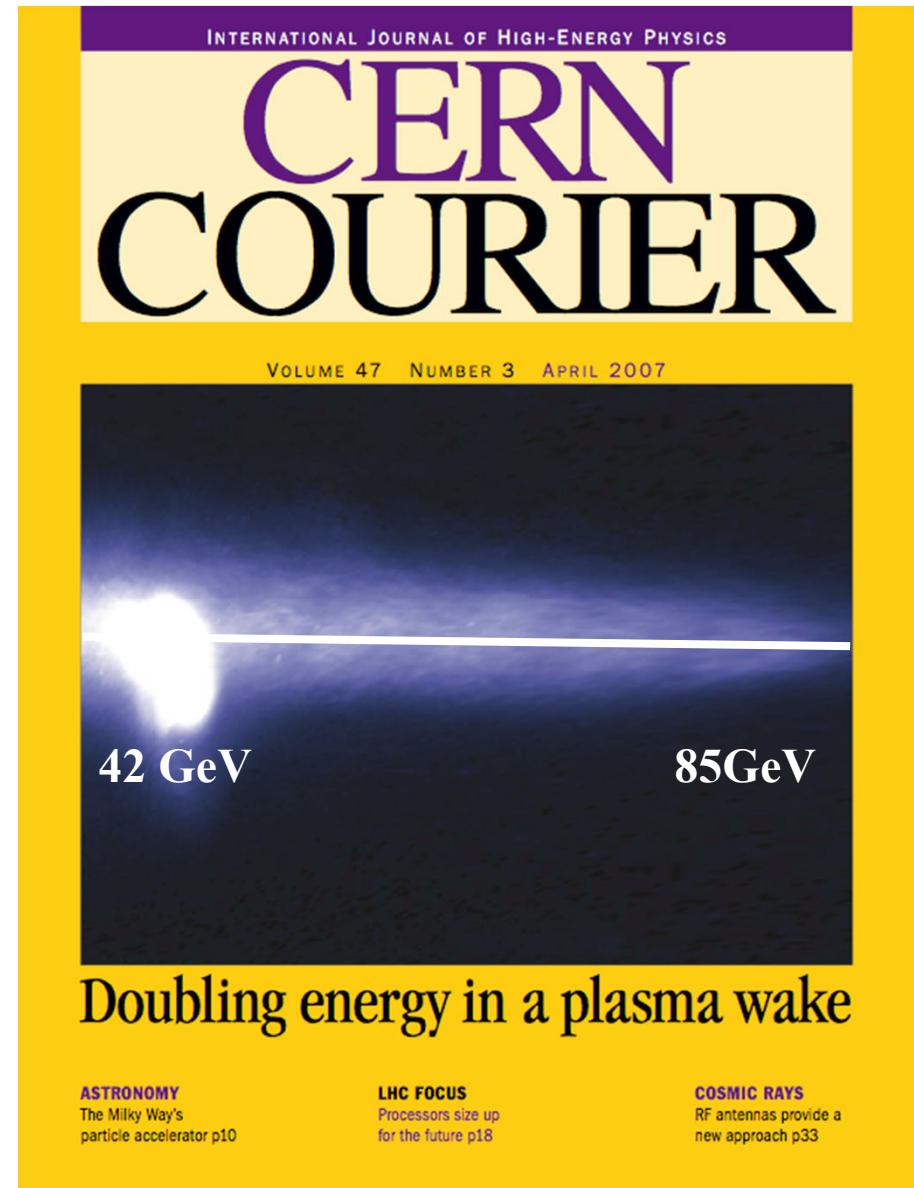


M.Hogan et al Phys Rev Lett (2005)
P.Muggli et al NJP 2010

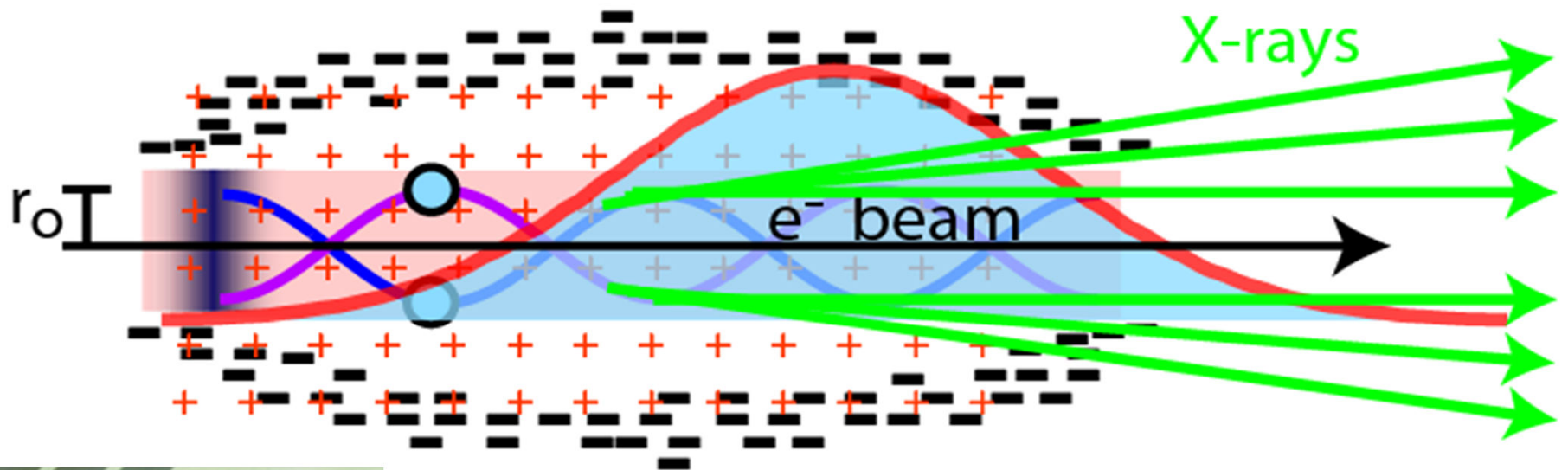
Path to a collider builds on recent success

- Energy Doubling of 42 Billion Volt Electrons Using an 85 cm Long Plasma Wakefield Accelerator

Nature v 445,p741 (2007)



Ultimate Limit on Plasma Accelerators: @ 3 TeV CM, with 1 micron beam, 10 GeV/m ~ 10% $\Delta E/E$ due to Radiation Loss



Plasma Wiggler for collimated X-ray production 10 KV-100 MV

$$\frac{dE}{dz} = \frac{1}{3} r_e m_e c^2 \gamma^2 k_\beta^2 K^2 = f(n_p^2, r_o^2, \gamma^2) = 4.3 \text{ GeV} / m$$

S. Wang et al. Phys. Rev. Lett. Vol 88. 13, pg. 135004, (2002), D.Johnson et al PRL 2006

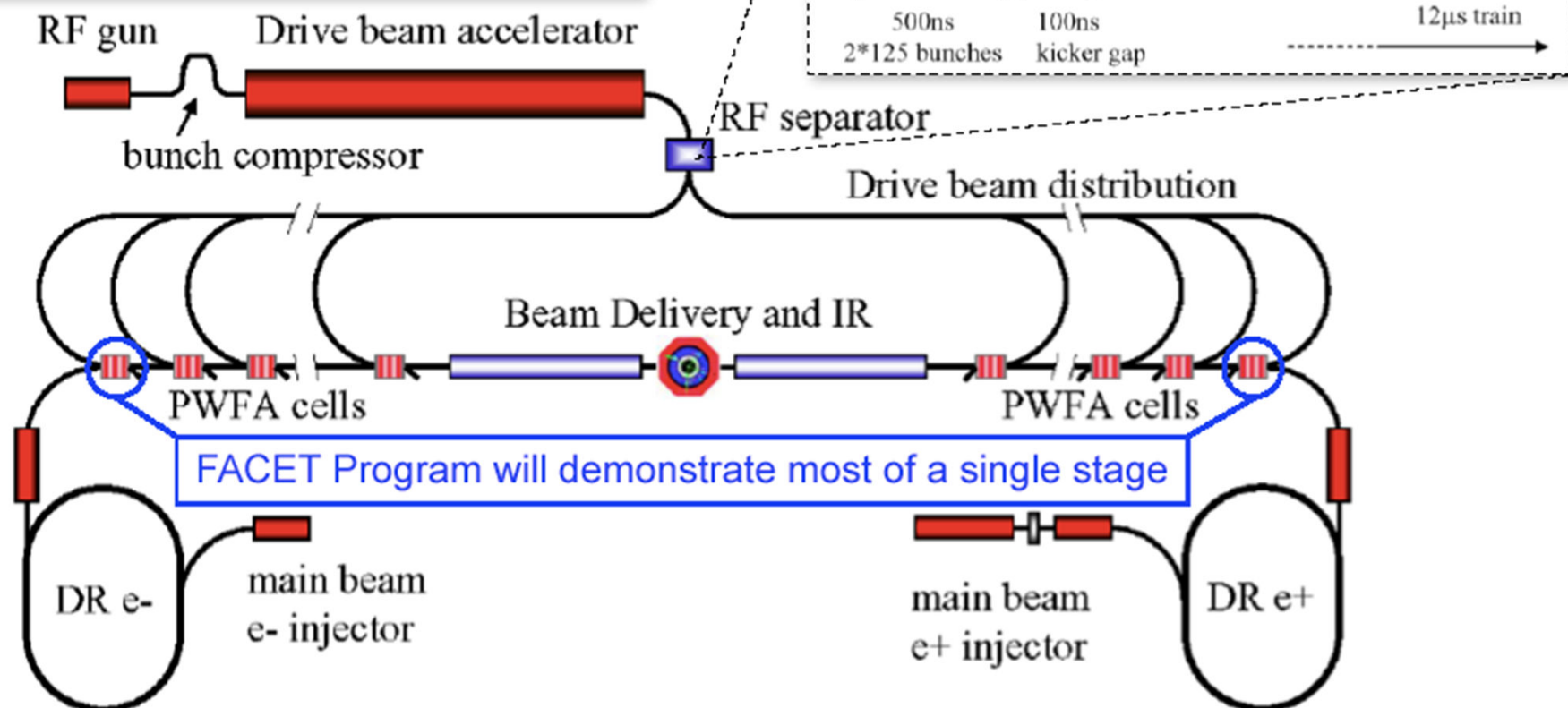
From Science to a Collider

Requirements for High Energy Physics

- * High Energy
- * High Luminosity (event rate)
 - $L = f_{\text{rep}} N^2 / 4\pi\sigma_x\sigma_y$
- High Beam Power
 - ~20 MW
- * High Beam Quality
 - Energy spread $\delta\gamma/\gamma \sim .1 - 10\%$
 - Low emittance: $\varepsilon_n \sim \gamma\sigma_y\theta_y \ll 1 \text{ mm-mrad}$
- * Reasonable Cost : less than \$5 B for 1 TeV CM
 - Gradients > 100 MeV/m
 - Efficiency > few %

A Concept for a Plasma Wakefield Accelerator Based Linear Collider

- TeV CM Energy
- 10's MW Beam Power for Luminosity
- Positron Acceleration
- Conventional technology for particle generation & focusing

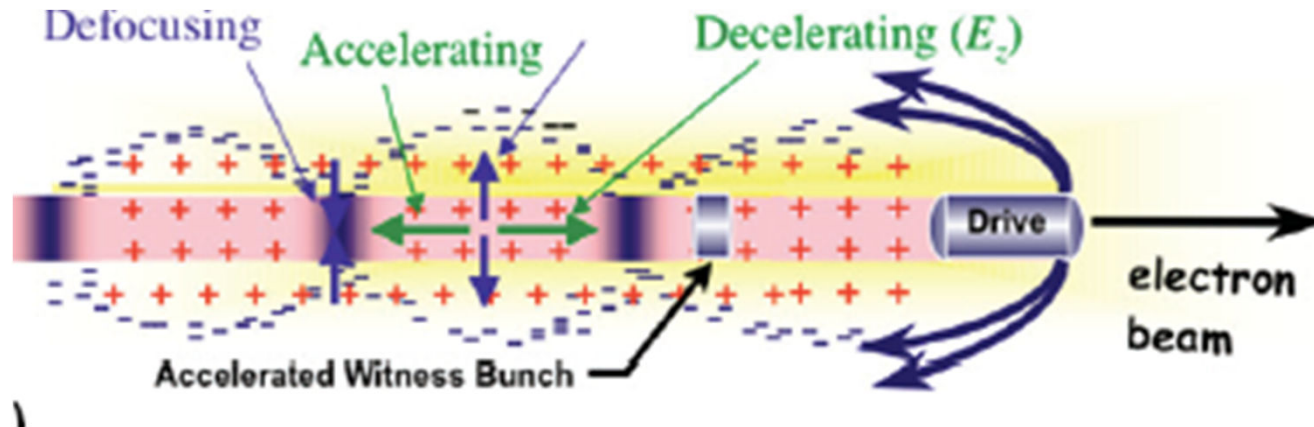


Self-consistent 1 TeV PWFA-LC Design

Luminosity	$3.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$	Small energy spread
Luminosity in 1% of energy	$1.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$	
Main beam: bunch population, bunches per train, rate	1×10^{10} , 125, 100 Hz	
Total power of two main beams	20 MW	Small Emittance
Main beam emittances, $\gamma\epsilon_x$, $\gamma\epsilon_y$	2, 0.05 mm-mrad	
Main beam sizes at Interaction Point, x, y, z	140 nm, 3.2 nm, 10 μm	
Plasma accelerating gradient, plasma cell length, and density	25 GV/m, 1 m, $1 \times 10^{17}\text{cm}^{-3}$	High Gradient
Power transfer efficiency drive beam \Rightarrow plasma \Rightarrow main beam	35%	
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 μs	
Average power of the drive beam	58 MW	High Efficiency
Efficiency: Wall plug \Rightarrow RF \Rightarrow drive beam	$50\% \times 90\% = 45\%$	
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW	
Site power estimate (with 40MW for other subsystems)	170 MW	

Demonstration of a Single Stage of a PWFA-LC

UCLA

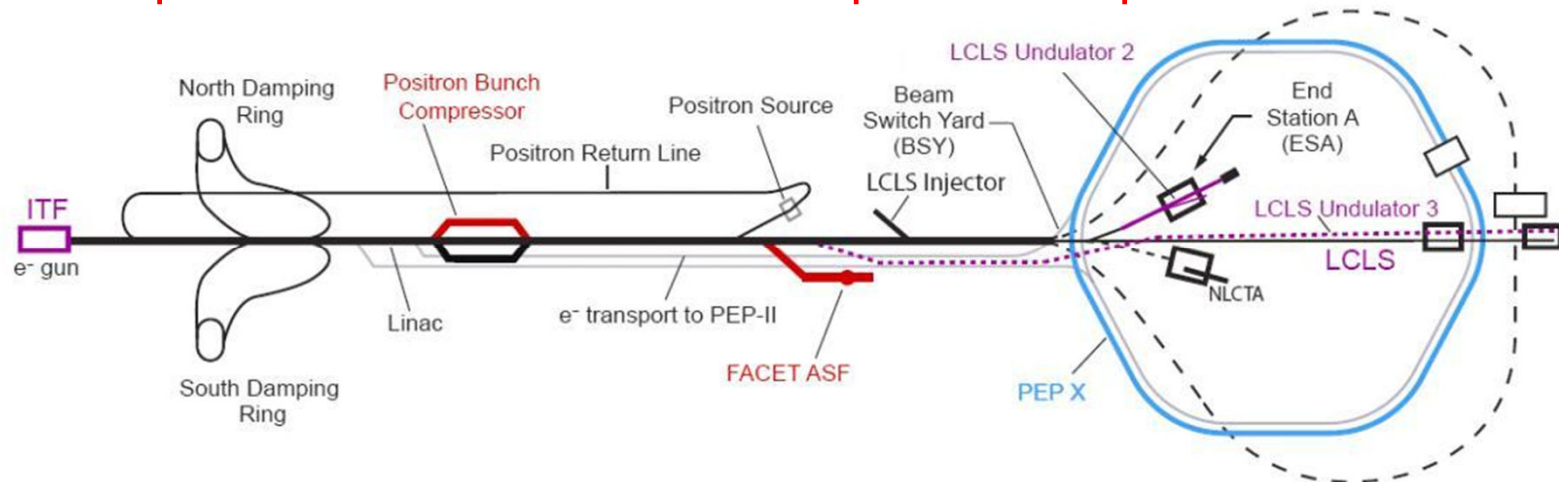


- 1) Accelerate a distinct second bunch containing a sufficient (100 s pC) char
- 2) Maintain the beam emittance
- 3) Produce a small (5-10%) energy spread
- 4) High (> 50%) energy extraction efficiency
- 5) Energy transformer ratio of greater than 1.
- 6) 25 GeV energy gain in 1-2 meters

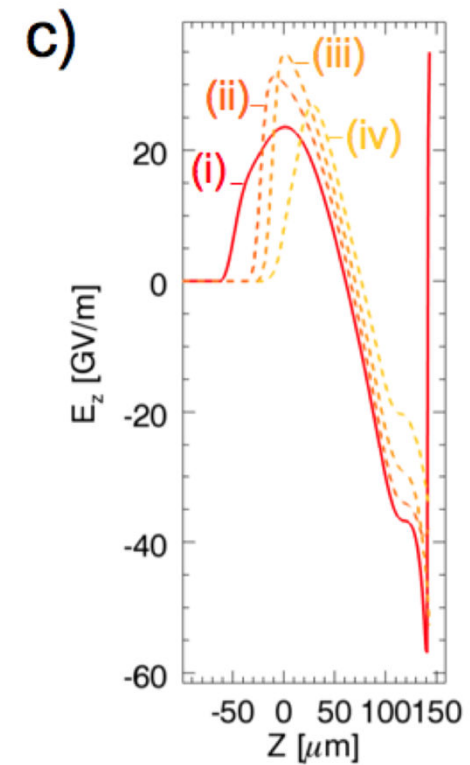
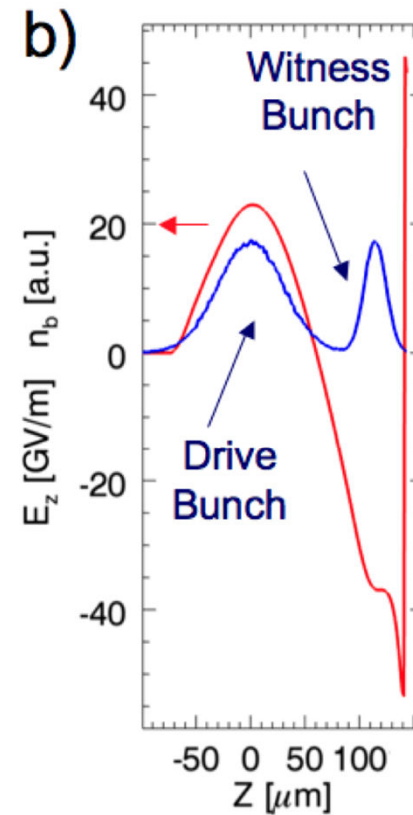
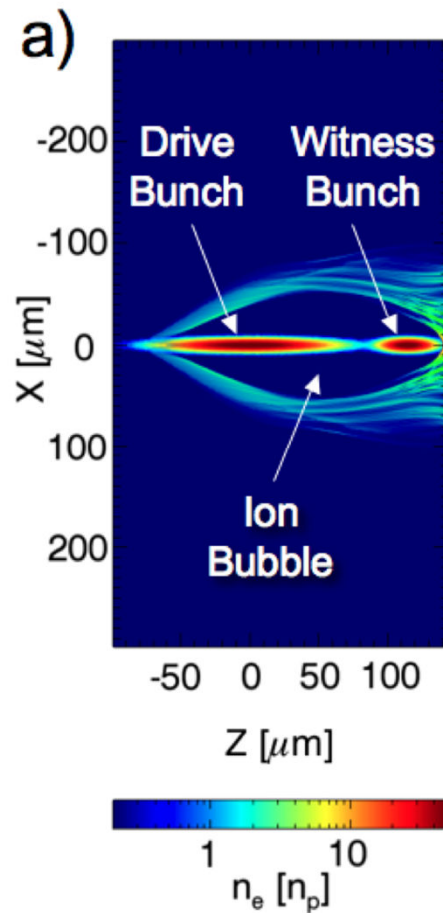
FACET PWFA Collaboration: Hogan, Joshi and Muggli: Cern Courier March 2011

FACET: Facility for Advanced Accelerator Experimental Tests

- * Use the SLAC injector complex and 2/3 of the SLAC linac to deliver electrons and positrons
 - Compressed 25 GeV beams \rightarrow ~20 kA peak current
 - Small spots necessary for plasma acceleration studies
- * Two separate installations
 - Final bunch compression and focusing system in Sector 20
 - Expanded Sector 10 bunch compressor for positrons



Ideal FACET experiment..

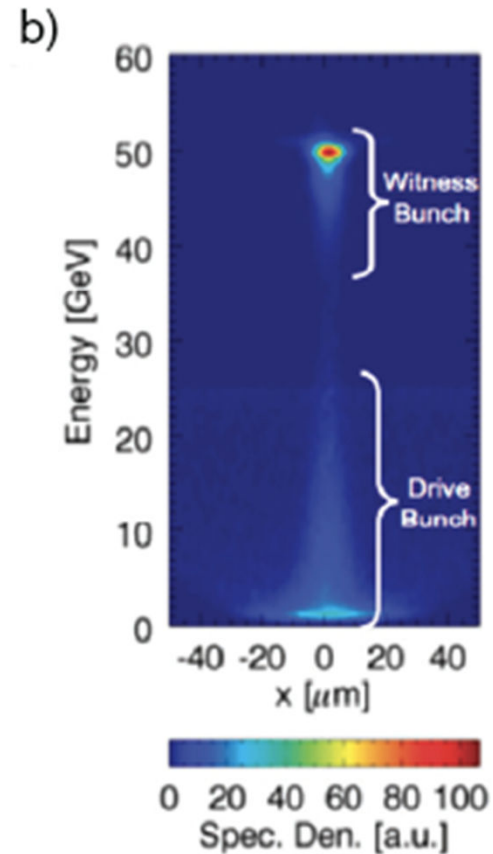
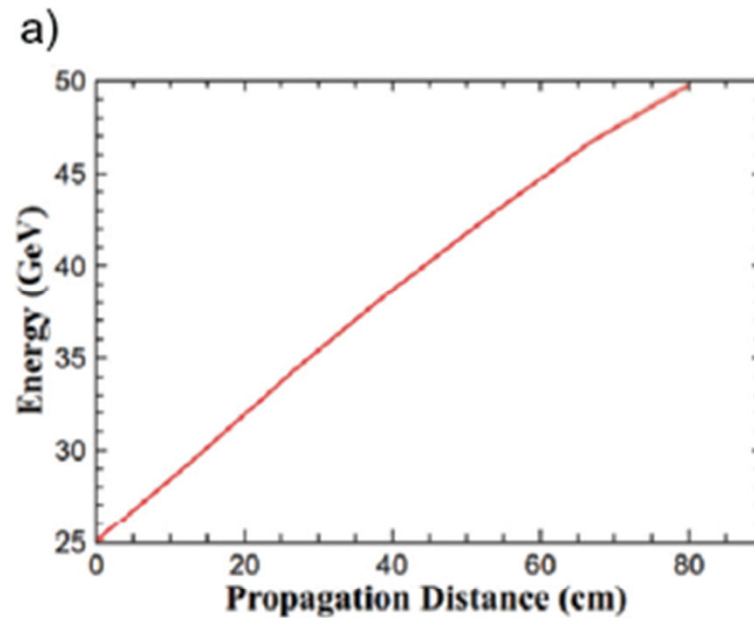


Transformer ratio of 2
Good beam loading efficiency

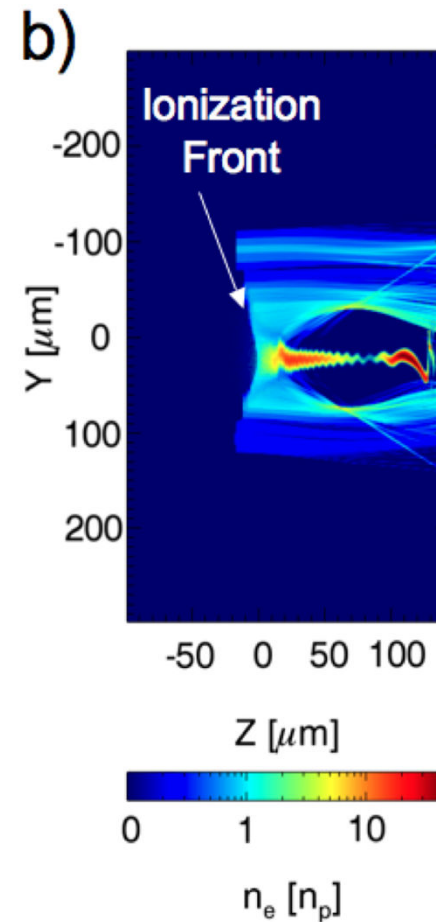
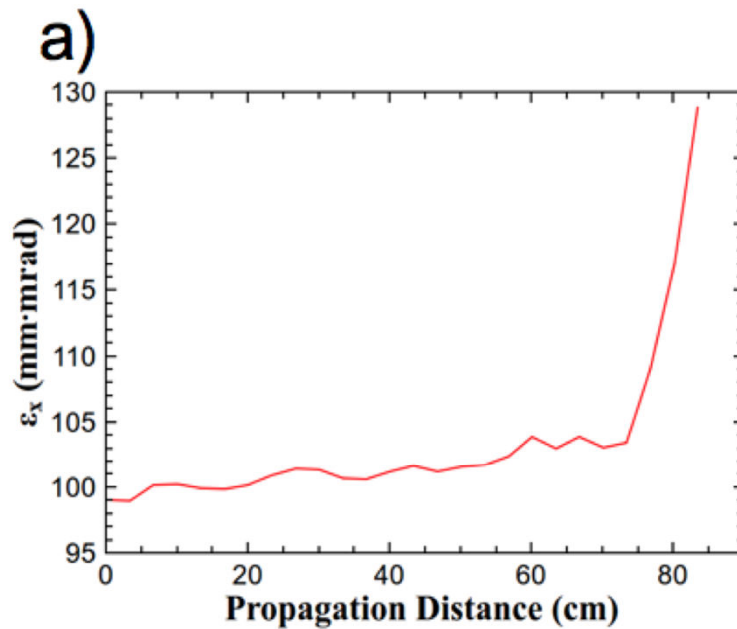
Drive Bunch
30 micron
3e10

Witness Bunch
10 microns
1e10

Energy Doubling of the Witness beam



Ideal FACET experiment...



Emittance preservation of the accelerating beam

Beam head erosion finally destroys the wake while hosing blows up the beam emittance

And What about Hadron Beams?

Pros:

Contain a great deal of energy

Possible to contemplate, again, a TeV class single stage PWFA afterburner

Cons:

Pulses are 10-30 cm long, compression to 100 microns seems expensive

First experiments will be in the self modulated regime

Need an electron injector to seed the wake and inject accelerated particles.

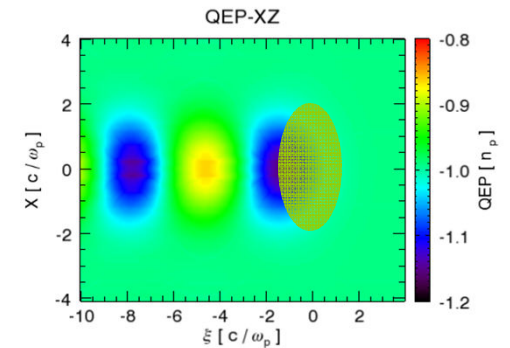
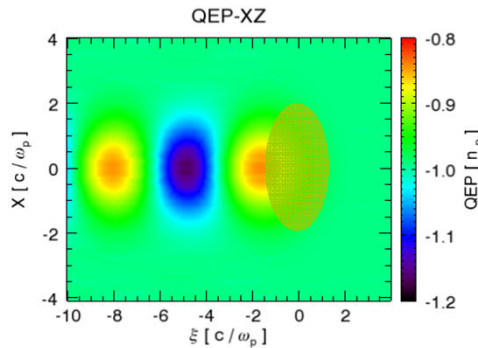
Linear wake fields driven by e^- and e^+/H^+ beams

e^- Beam

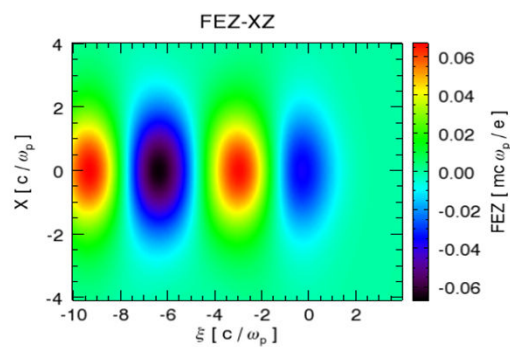
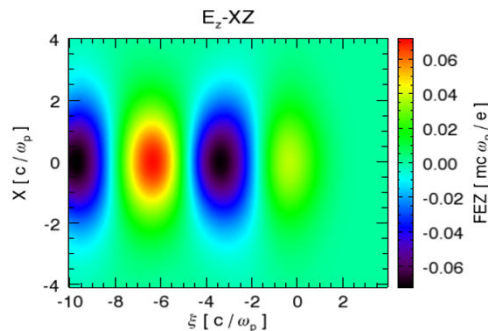
$n_b \ll n_p$

H^+/e^+ Beam

Plasma Density



Accelerating Field

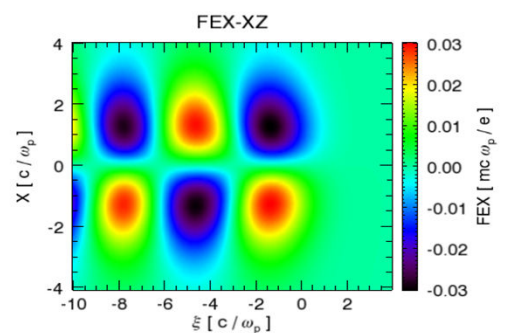
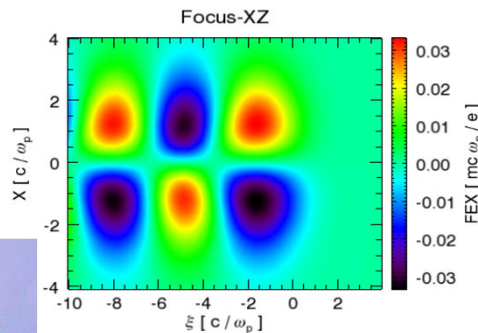


$$n_b = n_0 e^{\frac{-r^2}{2\sigma_r^2}} e^{\frac{-z^2}{2\sigma_z^2}}$$

$$\sigma_r = 1.0 k_p^{-1}$$

$$\sigma_z = 1.0 k_p^{-1}$$

Focusing Field



QuickPIC simulations

By Weiming An and Warren B. Mori UCLA

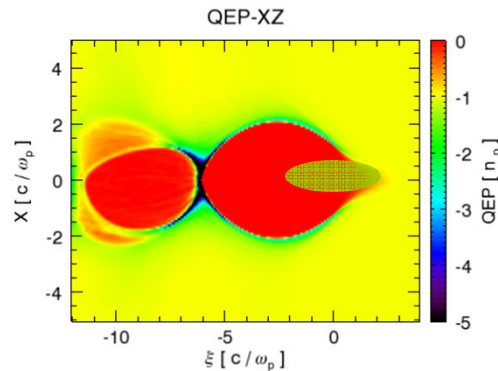
Nonlinear wakes driven by e^- and e^+/H^+ beams

e^- Beam

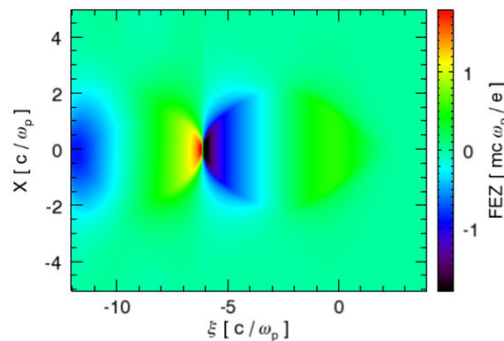
$n_b \gg n_p$

H^+/e^+ Beam

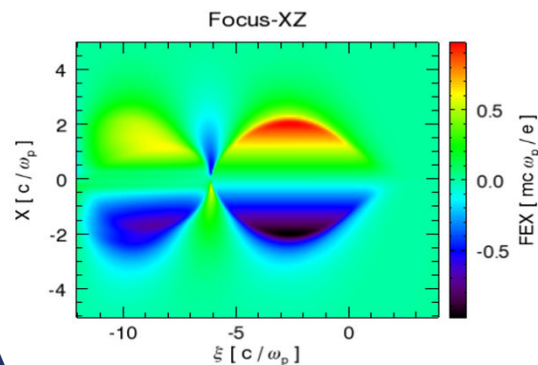
Plasma Density



Accelerating Field



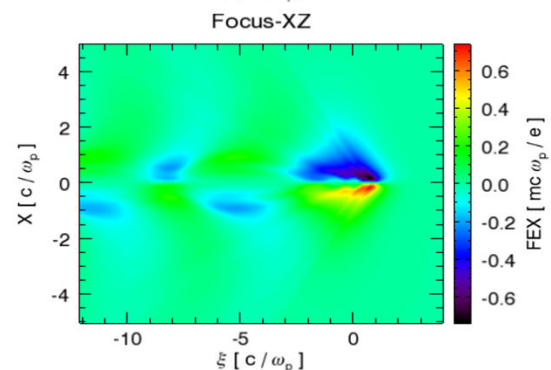
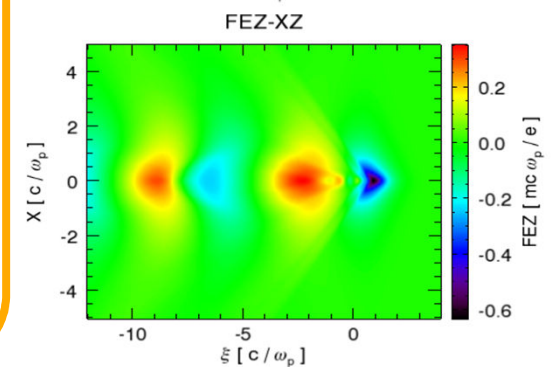
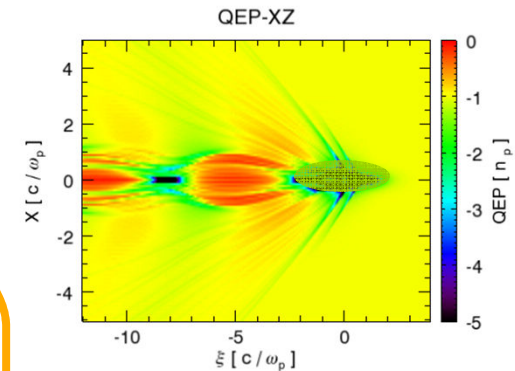
Focusing Field



$$n_b = n_0 e^{\frac{-r^2}{2\sigma_r^2}} e^{\frac{-z^2}{2\sigma_z^2}}$$

$$\sigma_r = 0.2 k_p^{-1}$$

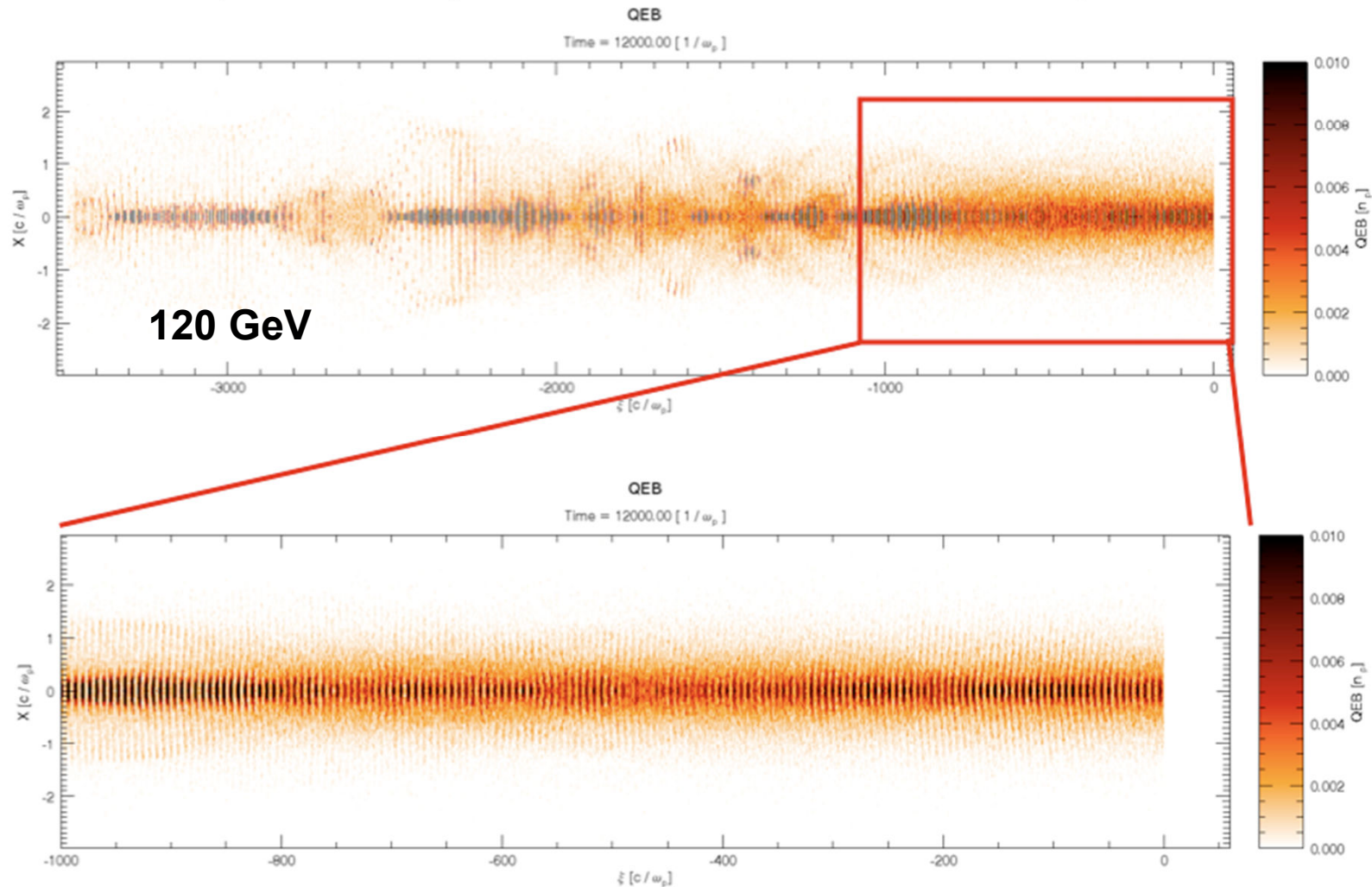
$$\sigma_z = 1.0 k_p^{-1}$$



QuickPIC simulations By Weiming An and Warren B. Mori UCLA

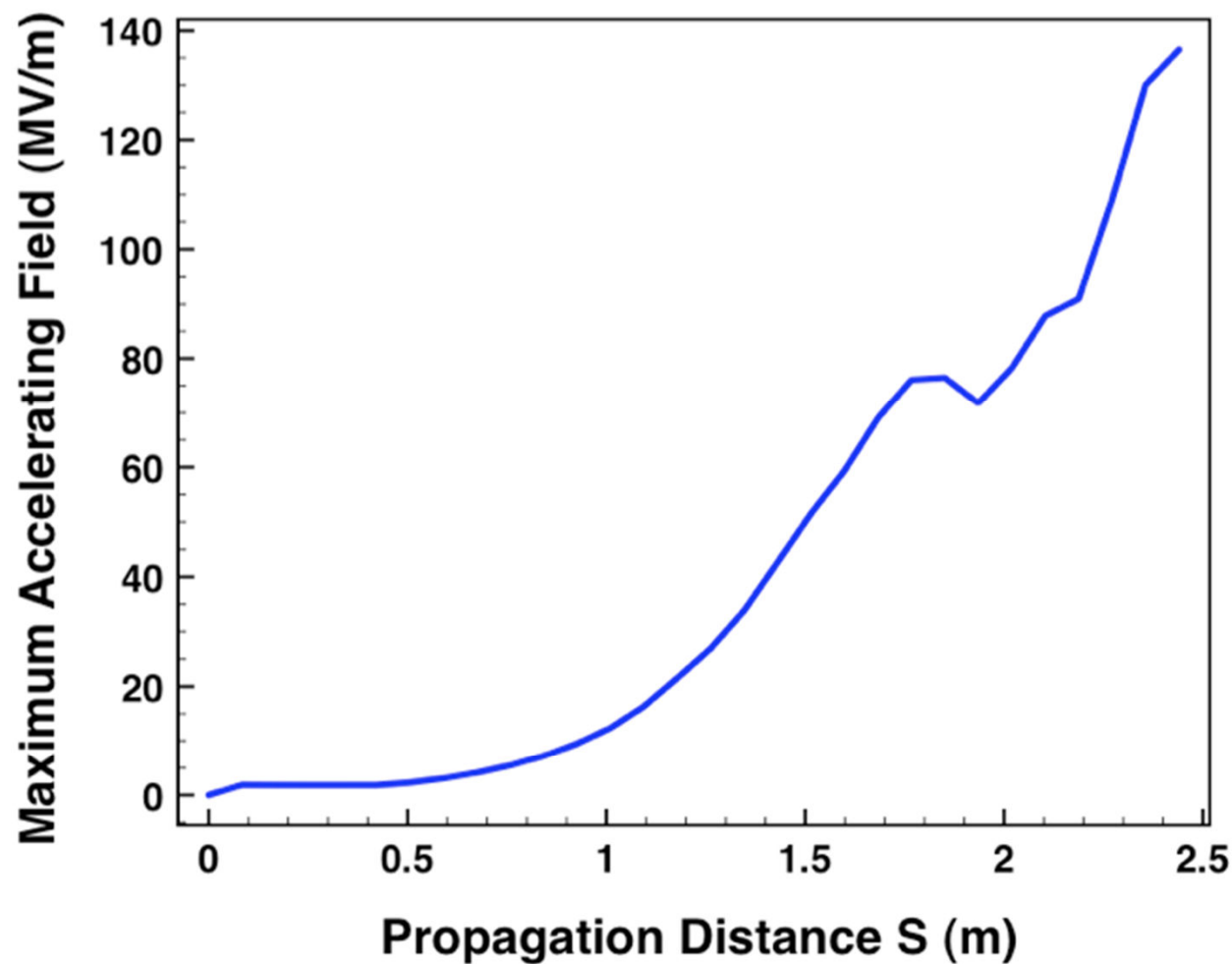
Self-Modulation of A Proton Beam

Beam : $\sigma_r = 100 \mu\text{m}$, $\sigma_z = 30 \text{ cm}$, $N = 1.0 \times 10^{11}$, Plasma Density : $1.0 \times 10^{15} \text{ cm}^{-3}$



Self-Modulation Of A Proton Beam

Beam : $\sigma_r = 100 \mu\text{m}$, $\sigma_z = 30 \text{ cm}$, $N = 1.0 \times 10^{11}$, Plasma Density : $1.0 \times 10^{15} \text{ cm}^{-3}$



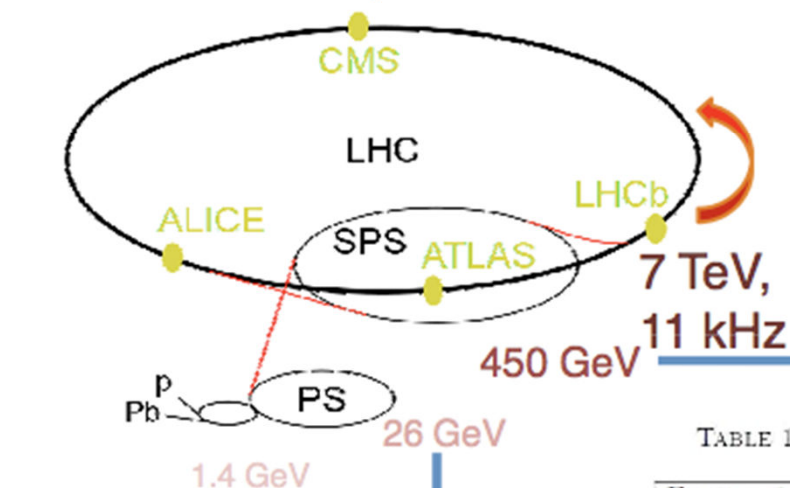
Reasonable Goals for a Proton-Driven PWFA

- * Demonstrate 1 GeV energy gain in 5 meters Using a 100 GeV, uncompressed beam at CERN/Fermilab
- * Demonstrate 100 GeV in 100 meters
 - * stability of drive beam
 - * small energy spread
 - * emittance preservation
 - * good beam loading efficiency
- * Demonstrate 500 GeV in 100 meters.

A 1 GeV in 5m Experiment at CERN : proposal stage

First hadron PWFA experiment will be in self-modulation regime

Possible driver parameters identified



SPS beam has advantages:

- 1) Less divergence
- 2) Initial beam density higher
- 3) More experimental space

But :

- 1) The beam is more stiff

PS beam :

- 1) Less stiff, faster instability growth

But :

- 1) Less experimental space
- 2) Instability growth limited by beam divergence

TABLE 1. Parameter Sets for Simulation Comparison

Parameter	Set 1	Set 2	Set 3	Set 4	Set 5
E_p (GeV)	24	24	450	450	450
N_p (10^{10})	13	13	11.5	11.5	3.0
σ_p (MeV)	12	12	135	135	80
σ_z (cm)	20	20	12	12	8
σ_r (μm)	400	400	200	200	100
σ_θ (mrad)	0.25	0.25	0.04	0.04	0.02
n_0 (cm^{-3})	10^{14}	$3 \cdot 10^{14}$	10^{14}	10^{15}	10^{15}
L_P (m)	10	10	10	10	10

Ref: PD-PWFA Collaboration: PI A.Caldwell MPI Germany

Summary

Plasma Wakefield Acceleration may be the way forward to a more compact and cheaper TeV class linear collider.

The driver technology – known for beam-driven PWFA.

SLAC is building FACET in response to DOE mission need to develop electron and positron acceleration in PWFA

Proton driven PWFA program has been proposed at CERN.

Still exciting science with low hanging fruit: arguably most exciting area of beam physics.

Fermilab with its hadron beams can play a critical role.

CONCLUSION

"The challenge is to undertake and sustain the difficult and complex R&D needed to enable a feasible , cost and energy effective technology on the several decade horizon . Achieving these goals will require creativity and the development and maturation of new accelerator approaches and technologies."

HEPAP

Marx Subpanel 2006

Ultimately the progress will depend on access to drive beam facilities